Sound Synthesis: A Flexible Modular Approach with Integrated Circuits

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Abstract

Recent interest in environmental art has generated a need for sophisticated but inexpensive sound synthesis and lighting control systems which can be manipulated by artists unfamiliar with electronics. A system philosophy that meets these requirements is described. Maximum flexibility through voltage control of audio variables by separate functional modules and input–output voltage compatibility among all the modules forms the basis of the system. Extensive use of integrated circuit technology offers low cost and high reliability. Specific examples of modules, including a complete description of one module (a voltage-controlled oscillator), are used to elucidate the system design philosophy. The 42 modules of 10 different types that were constructed demonstrate both the feasibility of the input–output compatibility approach and the advantages of integrated circuit technology.

I. Introduction

Studies in sound perception and growing interest in electronic music have led to the development of new approaches to sound synthesis. Digital control of all sound parameters is one of the most attractive approaches. Its two main advantages are the relatively easy creation of structurally complex pieces and exact reproducibility of effects. Unfortunately, the cost of digital control is still high despite recent price breaks, and rapid reprogramming or adjustment of sound parameters is often not possible.

By relaxing the requirement of complete digital control and, instead, using simple circuits of the analog computer type to perform voltage-controlled operations, one can construct at far smaller cost a hybrid modular system which retains many of the advantages of digital control. The instant access to all parameters made possible by such a hybrid system greatly enhances experimental and compositional modes of operation, especially where iterative adjustments are made to obtain the desired sound quality.

The sound synthesis system described here was designed for the Yale School of Art and Architecture for experiments in light and sound environments. This application called for sufficient flexibility to allow generation of 1) a single output with complexly structured sequence and spectrum, on the one hand, and 2) up to 10 channels of output of much simpler spectral composition but still sufficiently complex sequencing to generate program cycles of up to 30 minutes in "live" operation, on the other hand.

In subsequent sections, we will describe the system philosophy for a low-cost modular solid-state system, the module specifications in brief, and a few typical schematics as illustration of circuit design arising from the system considerations.

II. System Considerations

Modular sound synthesis systems utilizing the economy, reliability, and compactness of solid-state design are currently manufactured by the R. A. Moog Co.,[1] Trumansburg, N. Y., and Buchla Associates of Berkeley, Calif. These systems represent a great advance over earlier sound synthesizers, but do not as yet incorporate all possibilities of current technology. The design and construction of the present system takes full advantage of existing linear and digital integrated circuits. These devices permit considerable economy of design and wiring time and provide a significant improvement in performance and reliability over discrete component systems.

[1] R. A. Moog, "Voltage-controlled electronic music modules," *J. Audio Engrg. Soc.*, vol. 13, pp. 200–206, July 1965.

This means that even with modest facilities one can construct with confidence quite complex instrumentation.

The main features of the system designed for the Yale School of Art and Architecture are as follows.

A. Voltage Control

Voltage control is provided for all important parameters, such as 1) frequency, 2) amplitude, 3) attack and decay duration (independently), and 4) time interval generation by means of shift registers and other digital function modules.

The control voltage range is 0 to +3 volts, compatible with the linear and digital integrated circuits used in the design. Specifically, it was chosen to accommodate the logic levels of the resistor–transistor logic (RTL) circuits used. The extensive use of high-gain operational amplifier configurations ensures ample stability within this voltage range.

B. Elimination of the Distinction Between Signal and Control Voltages for Maximum Compatibility

The Buchla system, for instance, uses separate modules for signal and control functions. This leads to needless duplication of circuitry. For instance, 1) a "mixer" module will combine audio signals and another module will combine control voltages, yet both instances involve simply the addition of voltages, most simply done with an operational amplifier circuit; 2) so-called "ring modulators," basically small-signal analog multipliers, are used to generate beat frequencies, but are not usable for generating the product of control voltages.

In contrast, we aimed at maximum flexibility by designing modules all of which can accommodate frequencies from dc to 20 kHz at up to 3 volt amplitude. The output voltage swing of all "source" modules, such as voltage-controlled oscillators (VCOs), is between -3 and $+3$ volts. The wide frequency range of the VCOs allows them to function as sources of control voltage (in the range of 0.02 to 20 Hz) or as signal sources (in the range of 20 Hz to 20 kHz). Since all modules are dc coupled, all circuit functions are independent of frequency. Thus, a given VCO operating at a low frequency (say 2 Hz) might be used to frequency modulate another VCO (of identical design) operating at higher frequency, say 1000 Hz. Operational amplifier summers and inverters are used to scale and translate control voltages.

C. Low-Impedance Interconnections

All module output impedances are very low (generally about 0.1 to 1 ohm); all input impedances are in the range of 1000 to 4000 ohms. We have found it unnecessary to use shielded wire for patched interconnections, even in electrically noisy environments (e.g., SCR control circuits in fairly close proximity).

The utilization of simple pin jacks and plugs for all connections between modules also results naturally from eliminating the distinction between signal circuits and control circuits.

We hope to improve the interconnection scheme by a matrix of reed relays with address logic as soon as the necessary funds become available. All module inputs and outputs can be brought to the relay matrix from a rear connector on each module. The individual relays in the matrix would be digitally programmed from punched paper tape or magnetic tape.

D. General Purpose Potentiometers

As a deliberate design simplification, no means are provided within a module to set a certain parameter manually; instead, it is voltage controlled externally. For manual setting of sound parameters and for general use as amplitude controls, 60 potentiometers are presently provided on the front panel. These can be set individually to an accuracy of 3 percent of full scale and with a repeatability of 1 percent of full scale. Despite the use of simple carbon potentiometers, this accuracy is achieved by a technique familiar from analog computers. A double-pole double-throw pushbotton is associated with each potentiometer. Depressing the button places a $+3$-volt reference voltage across the resistance element, while a meter indicates the voltage between wiper arm and the grounded end of the resistance element as a fraction of full scale. Any load on the wiper arm (i.e., the input to a module) is left connected. This allows an accurate setting of the voltage division ratio under actual load conditions. Locating such potentiometers immediately below or above each module allows a direct association between the two, electrically as well as visually. To allow any potentiometer to be patched as an adjustable control voltage source, $+3$ volts is available on the potentiometer panels.

E. Ability to Modify External Program Material

While the modular system was designed for flexible "live" signal generation, this very flexibility also offers rich possibilities for modifying external audio material (e.g., taped signals, specialized waveform or noise generator outputs, or live sound pickup). The "modifier" modules (as opposed to the "source" modules, both to be described shortly) can perform amplitude modulation, beat frequency generation, signal routing, etc., on such external audio material. The combination of live signal synthesis with modified external inputs offers almost limitless possibilities.

F. Generation of Time Intervals and Fixed or Pseudo-Random Patterns by Shift Registers and Other Logic Circuitry

Up to 50 shift register stages are provided in the form of 5-stage modules. These can be cascaded or indepen-

dently operated. In the Buchla system, ring counters are provided which propagate a single ON state around a set of stages. Our shift register design permits not only such ring counter operation, but more generally the propagation of any pattern of ON and OFF states along a set of stages, whether arranged in an open chain or linked into a ring. Such patterns can be automatically regenerated or modified as desired. Special shift register configurations (e.g., the so-called Johnson counter) can be used to generate pseudo-random sequences.

In addition, OR and AND logic circuits are provided. Their use in conjunction with different sets of shift register stages allows formulation of timing sequences of great complexity. The shift pulses for shift registers can be obtained from voltage-controlled oscillators and voltage-controlled clocks (to be described below), as well as from any other shift register or logic circuit.

III. Module Specifications

The more specific implications of this general design philosophy can best be illustrated by brief description of the modules in the system at this time. Additional types of modules will be designed depending on future need, but the present set constitutes a valid nucleus for sound synthesis experiments.

A. Voltage-Controlled Oscillators

Ten such circuits have been constructed to date, in five modules. Each can be swept over three decades by a control input of 0 to 3 volts. While the basic range is 20 Hz to 20 kHz, external capacitors will allow lower frequency operation. For instance, an external 1 μF capacitor, patched into terminals provided, changes the range to 0.2 to 200 Hz. Both linear and logarithmic frequency control is available. Three output waveforms (sine, triangular, square) are simultaneously available. The output voltage excursion in each case is -3 to $+3$ volts. From the description of the VCO circuit (to follow), it will be seen that the slope of the output waveform is instantaneously proportional to the control voltage. Thus, there is no restriction on the frequency content of the control input. For instance, feedback from the square-wave output to the control input will produce controlled asymmetry of the output, allowing a type of voltage control of harmonic content in conjunction with a multiplier module (to be described).

B. Log Function Generators

These two-terminal diode–resistor networks are housed in a separate temperature-controlled module. Used as series elements feeding a control input summing junction on the VCOs, they provide stable logarithmic voltage-to-current conversion for logarithmic frequency control.

C. Voltage-Controlled Clocks

This is essentially a kind of special purpose VCO. The output frequency is voltage controlled over the range of about 0.2 to 10 Hz, and the available output waveforms are sawtooth and narrow pulse (both 0 to $+3$ volts). The latter is intended as a shift pulse for shift registers; the former can be used for frequency sweeps. The effect of a control voltage change on the output frequency is instantaneous (as is the case for the VCOs). This will be seen later to be of great usefulness in conjunction with the shift register modules. Five such circuits are available in one module.

D. Envelope Generators

This unit generates a general purpose trapezoidal waveform for use in amplitude or frequency modulation. The attack (0 to $+3$ volts linear rise) and decay ($+3$ to 0 volts linear fall) durations are independently voltage controllable over the range of 5 seconds to 8 milliseconds. The time intervals between the start of the attack and the start of the decay are determined by a gate input, usually obtained from a shift register stage. The system incorporates 10 envelope generators at this time (2 per module). External capacitors can be patched in to lengthen attack and decay to 50 or 500 seconds.

E. Multipliers

The multiplier circuits are of the four-quadrant type, with two inputs and one output covering the voltage range of -3 to $+3$ volts. Simultaneous pulse-height–pulse-width modulation of a 200-kHz square wave was used here, but the method is immaterial. Commercial four-quadrant multipliers well suited for this application are now available for under $150.[2]

Depending on the choice of inputs, the following functions can be performed.

1) Amplitude control (audio signal $\times$ control voltage): in this fashion an envelope generator waveform is imposed on a VCO output, for instance.
2) Beat frequency generation (one audio signal $\times$ another audio signal): this process of sum and difference frequency generation is useful for the synthesis of complex signals.
3) Frequency doubling: by connecting both inputs together and squaring a sine wave, frequency doubling occurs. The concurrent dc component can be removed with a coupling capacitor, or offset with an operational amplifier.
4) Manipulation of control voltages: envelope generator outputs can be squared for parabolic rise and fall, complex envelopes can be generated as the

[2] For instance, the model MU401, manufactured by the GPS Instrument Co., Newton, Mass.

product of individual envelope generator outputs, and so forth.

The fundamental usefulness of the multiplier circuit can hardly be overemphasized. Accordingly, 15 such circuits are at present available, 3 per module.

F. Operational Amplifiers

With a total of five inputs, each circuit generates the sum of the input voltages. The inputs are weighted so as to keep the sum from exceeding the 3 volt maximum.

It may be mentioned here that the VCO and the operational amplifier, amongst others, have another control input available in the form of an operational amplifier summing junction. By use of appropriate series resistors (available as plug-in elements), extra summing operations can be performed without the need for another operational amplifier module.[3] The use of high-gain amplifiers and precision resistors yields gain stabilities of better than 1 percent and output zero drift below 2 mV.

G. Inverters

These have one input, one summing junction, and one output available and can be used to convert a 0 to +3 volt transition to one from +3 to 0 volts, as would be needed for cross-fading. Eight inverters are contained in two modules.

H. Linear Gates

For purposes of signal routing, 12 of these bidirectional linear gates were designed into 3 modules. Each gate takes the form of a single-pole double-throw electronic switch controlled by a differential input. A given voltage source can be routed to two inputs, or a given input can select from two sources. Again, the dc coupling allows either audio signals, control voltages, or digital signals (to be discussed shortly) to be so handled. The gating is controlled by a differential input stage which decides, in effect, the sign of the difference of two control voltages anywhere in the range of −3 to +3 volts. The actual switching is done by metal-oxide field-effect transistors (MOSFETs). Again, such circuits are now available entirely in integrated circuit form.

I. Shift Registers

As mentioned earlier, 10 modules are grouped 5 stages per module. Each stage has individual set and reset inputs and complementary buffered outputs. The inputs to the module as a whole consist of the logical inputs to the first stage (the J and K inputs), a buffered shift-pulse input, and a common set–reset input which forces all stages into an ON–OFF configuration chosen by toggle switches in each stage. Inputs and outputs on this and all other digital modules assume only two values, 0 and +3 volts. The shift registers are basic to the operation of the system, providing timing and sequencing functions, but in the interest of brevity only some applications will be given.

1) A certain fraction of the "yes" output from each stage is obtained by potentiometers. These voltages are added by an operational amplifier, the output of which controls the frequency of a voltage-controlled clock. The clock's pulse output, in turn, acts as the shift pulse for the shift register. For simplicity, let the shift register be operated as a five-stage ring counter (i.e., one ON state propagates around the five stages). Immediately following the shift pulse, the new state of the shift register determines the control voltage input to the voltage-controlled clock, thus determining the time interval until the next shift pulse. This is possible because of the instantaneous response of clock period to control input.

This arrangement allows independent adjustment of the ON duration of each shift register stage (0.1 to 5 seconds for potentiometer from minimum to maximum). (See Section III-C for a description of the voltage-controlled clock.)

Other sets of five potentiometers, summed by an operational amplifier, can generate stepwise varying control voltages for simultaneously associating a frequency or an amplitude with each shift register state.

2) Timing cycles within timing cycles can be created by using the output from one stage of a shift register loop as the shift pulse for another loop. These loop connections can be "simple" or "twisted" or more specialized, such as in the "Johnson counter" configuration which is useful for pseudo-random sequence generation.

3) Linear gates, when driven from shift registers, can generate complex routing sequences for audio signals and control voltages. A given sequence of control voltages, as generated in 1), could be used, in turn, to determine a sequence of frequencies, amplitudes, or time-intervals by routing to a VCO, a multiplier, or a voltage-controlled clock, respectively.

J. Other Logic Circuits

The system also contains several modules of AND, OR, and NOR circuits. They can be used to "recognize" certain shift register configurations (e.g., for purposes of initiating a new timing cycle), or to set up mutually exclusive shift patterns among the shift register modules.

It should also be recalled that the differential input of the linear gates allows them to make decisions regarding the amplitude relationships amongst the control voltages determining the characteristics of the synthesized signal(s). These decisions can determine the routing of digital or analog signals. The logic circuits and linear gates provide

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[3] The log function generator can also be connected to the summing junction of the operational amplifier to convert a linear 0 to 3 volt change into an exponential one. This generates the control voltage for exponential amplitude control with a multiplier.

the means for logical decisions among the discrete as well as continuous variables of the system.

This survey of the constituent elements of the system is not particularly intended as a description of a desirable system configuration, but as an example of the many possibilities inherent in a design philosophy based on maximum compatibility among modules. The design of additional types of modules, such as voltage-controlled filters, envelope generators with greater than 500-second rise and fall times, etc., is under consideration to fulfill anticipated needs in our particular application of signal synthesis for experiments in light and sound. Other users of such a system may be interested in a considerably different emphasis among the modular functions.

IV. Circuit Design Examples and Construction Details

The modular functions described here are not unique to a particular circuit. Many different designs could be used with essentially equal validity. In all cases, the availability of a wide range of integrated circuits permits the designer to concentrate on system aspects such as compatibility among modules. In our case, the generous contribution to this project of particular types of integrated circuits by the Radio Corporation of America and the Fairchild Semiconductor Corp. set the framework for our design. As an illustration, we will describe briefly the block diagram and the actual circuit of the VCO.

The block diagram is shown in Fig. 1. The output of the integrator is monitored by a Schmitt trigger circuit with triggering points determined by a symmetrical temperature-stable Zener diode and associated resistors. The Schmitt circuit is indicated as symbolically operating a current mode switch which reverses the polarity of the charging current to the integrator. The magnitude of the charging current is determined by the current supplied to the input summing junction. The frequency of the output is proportional to this input current, which is generated either by a series resistor or a log function generator (neither shown) for linear or logarithmic frequency control.

The complete version of the circuit is shown in Fig. 2. The operational amplifiers used are either RCA type CA3015 or the simple configuration shown at the lower right, using a type CA3018 as a dual Darlington input stage.

The output of the integrator is buffered with one half of a type CA3036 dual Darlington which has higher current handling capabilities than the CA3018. The Schmitt trigger is formed with another CA3015 operational amplifier and an output stage formed by the complementary common emitter stages Q1, Q2. The resulting 30 volt peak-to-peak square wave has already excellent amplitude stability due to the saturated switching of Q1 and Q2. The additional clipping to a 6.2 volt reference level by the type F16H1 (General Electric) Zener diode and the high gain of the CA3015 operational amplifier set the trigger points

of the Schmitt circuit at −3 volts and +3 volts with a stability of better than 0.1 percent under normal operating conditions.

The current switching at the integrator summing junction is conveniently done with the type CA3019 diode array, containing D1, D2, D3, D4, and D5. The forward voltage drop of all diodes was found to be matched to within 1 mV for forward currents from 1 μA to 3 mA. The bridge configuration serves as the current mode switch, selecting between the equal and opposite currents generated by the 680 ohm resistors. D1 in the feedback of operational amplifier #1 provides exactly the right additional voltage to cancel the effect of voltage drops in D2, D3, D4, and D5 on the integrator charging current. The matching of the 680 ohm resistors ensures that the current supplied to the input summing junction is equal in magnitude to the integrator charging current. Resistor R is chosen to give 20 Hz output frequency in the absence of a control input current. An input of 3 mA will give a frequency of about 21 kHz. In actual operation, 1 kΩ resistors are patched in for linear frequency control or, more frequently, a logarithmic voltage-to-current converter, housed in a separate temperature-controlled module, is connected to the input.

The sine-wave output is obtained by diode function generation from the triangular wave. The procedure is well known and need not be discussed further. The total harmonic distortion is below 3 percent and could readily be improved by more elaborate function generation.

The frequency stability is limited by the current and voltage input offset of operational amplifier #1. Temperature-dependent offsets in the present low-cost configuration result in drifts of several Hz for limited changes in ambient temperature ($\pm$5°C), sufficient for our purpose, but readily improved by higher-quality operational amplifiers such as additional CA3015 in the control input portion of the circuit.

Fig. 3 shows an overall view of a VCO module, containing two circuits as described earlier. The printed-circuit board dimensions are $4\frac{1}{2}$ by 6 inches, and the module width is 1 inch. This is the standard size of all modules except the shift registers, where the number of panel connections and switches necessitated a 2 inch width. In each module, the back edge of the printed-circuit board is shaped into a connector for power connections, but also for bringing inputs and outputs to a programming matrix at a future date.

The compact size of the individual modules allows the system as described to be contained in 28 inches of rack-space, as seen in Fig. 4.

It should be mentioned that once the printed-circuit layout itself is designed, the assembly can proceed with semiskilled labor. In the interest of maximum economy, all the circuit cards in the present project were assembled by artists and student wives with essentially no previous experience in electronics. The incidence of mistakes was quite low.
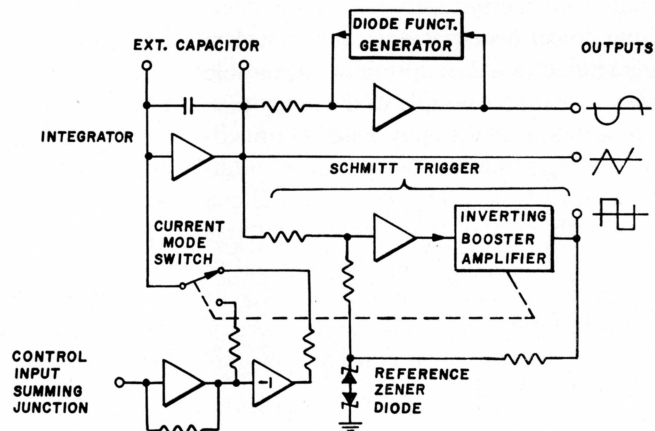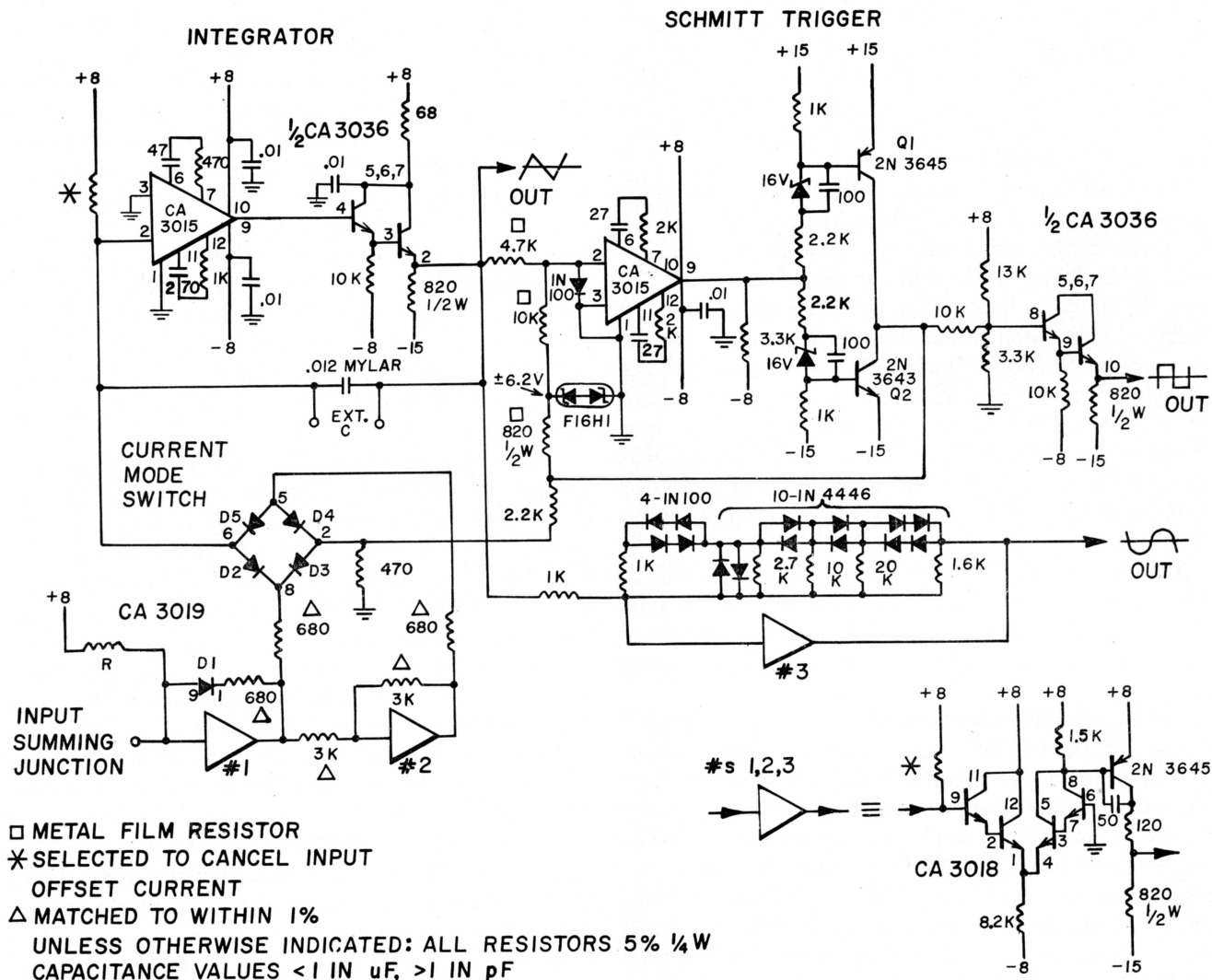
Fig. 1. Block diagram of the voltage-controlled oscillator (VCO).

Fig. 2. Actual schematic of the voltage-controlled oscillator (VCO).
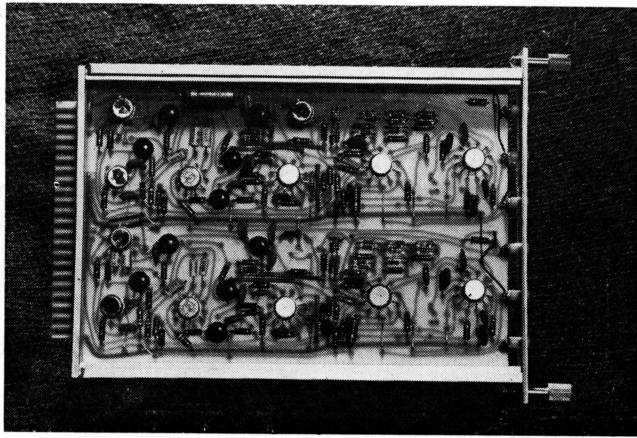

□ METAL FILM RESISTOR
✳ SELECTED TO CANCEL INPUT
  OFFSET CURRENT
△ MATCHED TO WITHIN 1%
  UNLESS OTHERWISE INDICATED: ALL RESISTORS 5% ¼W
  CAPACITANCE VALUES <1 IN uF, >1 IN pF

Fig. 3. Side view of a dual VCO module. The mounting frame is manufactured by the Vector Electronics Company and has dimensions of $5\frac{1}{2}$ inches high by 1 inch wide by $6\frac{1}{4}$ inches deep.

(A)
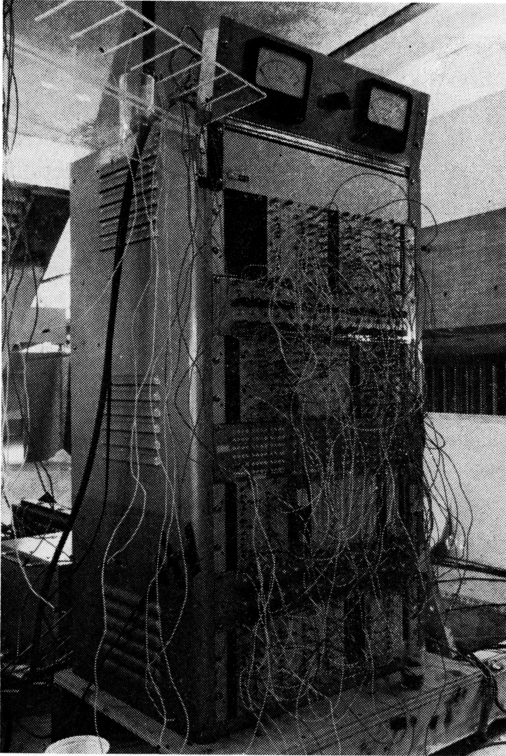
Fig. 4. (A) The complete modular system. Note the two sets of general-purpose potentiometers. The digital modules are in the bottom rows. The modules are inserted into frames and are freely interchangeable, allowing the choice of configuration most suitable for a given synthesis experiment. (B) A closer view of a set of modules. Above, the potentiometers, each with a pushbutton as described. The modules below are, from left to right: dual VCO module, log function generator, two more dual VCOs, dual operational amplifier, quadruple inverter, and three dual envelope generators. At the extreme right, one of the quadruple signal gates.

(B)
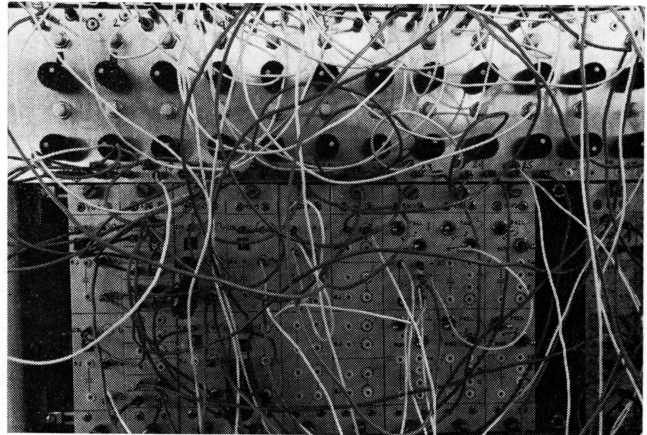
V. Conclusion

The current availability of low-cost digital and linear integrated circuits offers considerable advantages in the area of low-cost sound synthesis. Since individual circuit functions are largely prepackaged, the designer can concentrate on a unified approach to the system functions. The actual circuit details are generally straightforward and can lean heavily on the applications literature of integrated circuit manufacturers. Breadboarding phases in the design are often completely eliminated, cutting total

development time considerably. Less than three months elapsed in the present instance between start of design and final testing of all modules. Finally, since the input–output compatibility among modules leads to simple rules for interconnection, we have found that nontechnical people can readily learn the patching procedures which are required until automatic programming features are incorporated. Thus, use by technically unskilled personnel should not deter designers from using the flexibility of a patching scheme as the first stage in the evolution of a modular sound synthesis system.
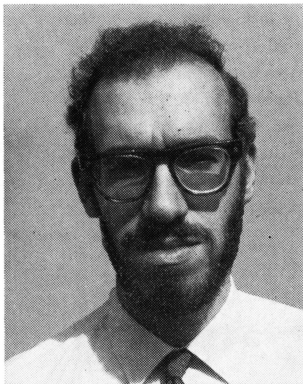
Peter J. Kindlmann (S'61–M'66) was born in Vienna, Austria, on June 4, 1939. He received the A.B. degree from Columbia University, New York, N. Y., in 1962, and the M.S. degree in physics and the Ph.D. degree in engineering and applied science from Yale University, New Haven, Conn., in 1964 and 1966, respectively. His doctoral dissertation involved research in atomic physics, in particular the measurement of excited atomic state lifetimes of interest in connection with gas laser systems.

Since 1966 he has continued to be associated with the Dept. of Engineering and Applied Science at Yale as Lecturer, Research Associate in the laser group, and Director of the Electronics Laboratory which he organized in 1965. In the last connection, he has explored the application of electronic instrumentation to diverse research activities at Yale, including plasma physics, biophysics, medicine, and art. His association with a group of research associates in the Yale School of Art and Architecture led to the design of the present sound synthesis system.

Dr. Kindlmann is a member of the American Physical Society, the American Orchid Society, Sigma Xi, and Phi Beta Kappa.
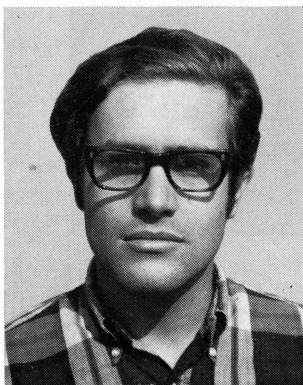
Paul H. Fuge was born in Plainfield, N. J., on June 9, 1946. He received the B.A. degree in psychology from Yale University, New Haven, Conn., in 1968.

At present he is employed by Yale University as a Research Associate in the arts. For the past year he has been a member of Pulsa, a group of artists and engineers interested in environmental art. Pulsa exhibited work in the spring of 1968 at the Yale School of Art and Architecture and in the fall of 1968 outdoors in and around the pond in the Boston Public Garden, Boston, Mass.